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Design of Photonic Topological Insulators Using Density Based Topology Optimization

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Abstract

We provide a novel photonic topological insulator design (PTI) exhibiting the quantum-spin-Hall effect, which, as opposed to previous designs, is conceived using numerical optimization of the transmission through PTI edge states. Specifically, we use topology optimization to maximize the transmission of light through a carefully configured model domain composed of two photonic crystal phases. This leads to a numerically generated PTI, which features larger bandgaps than previously predicted for planar PTIs and excellent suppression of backscattering from sharp bends.

1. Introduction

Time-reversal-invariant photonic topological insulators (PTIs) support pseudo-spin-dependent edge states with bi-directional propagation and robustness against certain classes of disorder [1, 2]. Such properties are obviously desirable in many applications in chip-scale photonics where controlled propagation and low losses are essential. However, designing a PTI is highly non-trivial as it requires inversion of band symmetries around a band gap and thus the designs for dielectric planar PTIs available in the literature have so far been obtained using cleaver ideas and painstaking trial and error [3, 4, 5] . We present a completely different approach to the design of PTIs where the problem is formulated as an inverse problem which we solve using density-based topology optimization [6, 7, 8]. Our approach allows tailoring PTIs for different figures of merit, such as operational wavelength, bandwidth, transmission, etc. Further, our approach allows for imposing any symmetry in the constituent unit cells among other possibilities.

This talk provides a brief description of the topology-optimization method, an in-depth description of the proposed design procedure, and analyses of selected PTIs, designed using the proposed approach.

2. The Method

A classical electromagnetic model is assumed for the light,

$$\nabla \times (\nabla \times \mathbf{E}(\mathbf{r})) - k_0^2 \epsilon_r(\mathbf{r}) \mathbf{E}(\mathbf{r}) = \mathbf{S}(\mathbf{r}), \quad \mathbf{r} \in \mathbf{\Omega} \in \mathbb{R}^2.$$

with $\mathbf{E}$ denoting the electric field, $k_0 = \frac{2\pi\nu}{c}$ the free-space wave number with ν being the frequency and c the speed of light in vacuum, ϵ_r the relative permittivity and $\mathbf{S}_e$ a source. The two-dimensional model domain $\mathbf{\Omega} \in \mathbb{R}^2$ is truncated using a perfectly matched layer [9].

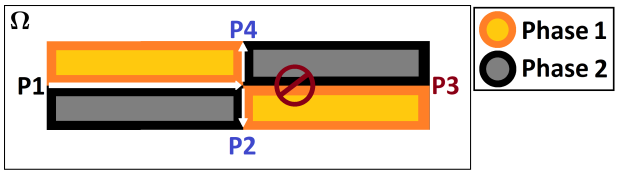

Figure 1: Conceptual sketch of the design-model domain, $\mathbf{\Omega}$. The edge (bulk) of the PC phases constituting the PTI are colored orange (yellow) and black (grey). The input/output ports are denoted P1-P4 and the arrows indicate power flow.

The PTI structure consists of two periodic hexagonal photonic crystals (PCs) with a zig-zag interface. In the design problem, the two PCs are placed in $\mathbf{\Omega}$ as sketched conceptually in figure 1. The problem of designing the PTI is formulated as an inverse problem and solved for a set of frequencies using density-based topology optimization [6]. In the design process, the material configuration constituting the PCs is changed iteratively in order to simultaneously maximize the transmission of energy from P1 to P2 and P4 and minimize the transmission to P3 while ensuring that both PC phases exhibit bandgaps at the targeted frequencies by enforcing a set of inequality constraints. By achieving negligible transmission from P1 to P3 and high transmission from P1 to P2 and P4, a behaviour identical to that of a PTI, configured as shown in figure 1, is obtained.

After the design procedure is completed, the band-structure for a supercell containing both PCs and their interface is computed. This is done to validate that a pair of counter-rotating pseudo-spin edge states exists inside the bulk-bandgap region at the targeted frequencies, confirming the successful design of a time-reversal invariant PTI.

3. Discussion

A PTI consisting of a silicon membrane ($\epsilon_{\mathrm{r,Si,reduced}} = 9.61$) with air holes ($\epsilon_{\mathrm{r,air}} = 1$) is designed using the proposed

approach. Both PC phases are initiated from the structure shown in figure 2**A**, C_{6v}-symmetry is imposed on the PC unit cells, and the frequencies $\nu \in \{184\text{ THz}, 187\text{ Thz}\}$ are targeted in the design process. The two PC phases constituting the final PTI design are shown in figure 2**B**-2**C**.

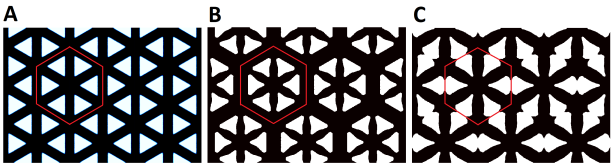

Figure 2: **(A)** Initial and **(B-C)** final distribution of Si (Black) and air (white) for the PCs constituting the PTI. The hexagonal unit cell is outlined in red.

In order to demonstrate the directional pseudo-spin dependent energy transport supported by the PTI, a chiral TE-polarized dipole source is placed at the interface between the two PC phases while varying the chirality from clockwise to counter-clockwise. The $\mathbf{H}_z$-component of the resulting field (shown for $|\mathbf{H}_z| > 0.05$) is plotted in figure 3**(A)** and 3**(B)**, respectively. It is clearly seen that the right-handed (left-handed) chirality excites the edge state with positive (negative) pseudo-spin travelling to the left (right).

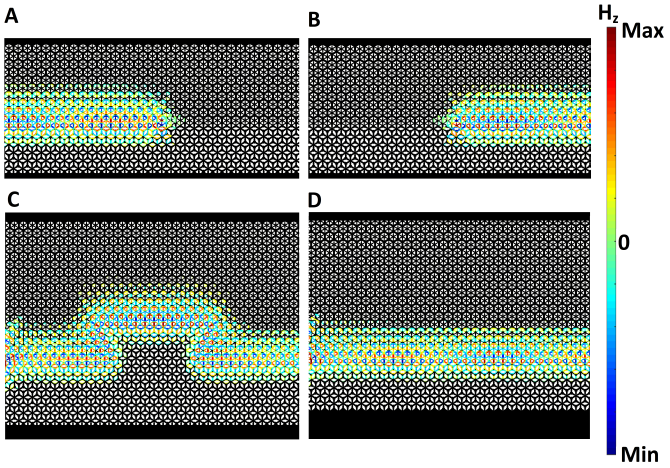

Figure 3: **(A-B)** Chiral emission for **(A)** clockwise and **(B)** counter-clockwise excitation. Field propagation along the PTI interface **(C)** past four 120^o bends and **(D)** along a straight channel. The H_z-field component is shown for $\nu = 184$ Thz, overlaid on the PTI-structure.

A numerical demonstration of the back-scattering robustness offered by the PTI is shown in figures 3**C** and 3**D**. The former showing a field propagating along the PTI interface from left to right past four 120^o bends and the latter showing a field of equal amplitude propagating along a straight edge. From the figures it is seen that negligible back-scattering occur at the bends, in fact an energy loss of less than 0.07 dB per bend is computed. In a further set of calculations (not shown) we find that the relative bandgaps of the two crystal phases are 19% and 6% and we obtain a directional beta-factor $> 99\%$. [10]

4. Conclusion

A novel PTI is proposed and analysed along with the topology-optimization-based approach used in its design. The resulting structure features large bulk bandgaps, very low bending losses, and a very high degree of direction emission. The proposed design approach may be used to devise novel PTIs and/or to tailor them to maximize different figures of merit, such as operational bandwidth and/or energy transmission.

Acknowledgement

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